

CF3 Summary
Non-WIMP Dark Matter
Cosmic Frontier Summary Talk

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Recap: Meetings & discussions over the year

This Snowmass is the culmination of a series of workshops. Besides from the Snowmass-wide and CFn-wide meetings at SLAC & FNAL, there's ...

SnowBird UT 22-25 March 2013. "SnowDark" meeting. "The workshop will focus on the theoretical motivation, physical properties, detection techniques, and experimental searches for a broad range of well-motivated dark matter candidates. This will feed into the Non-WIMP dark matter subgroup of Snowmass."

Seattle WA 23-26 April 2013. "This workshop will (1) organize much of the scientific foundation for the next generation of axion and axion-like-particle (ALP) experiments and searches, (2) and will be a roadmap for the researchers, research sponsors and the broader scientific community. This will feed into the Non-WIMP dark matter" subgroup of Snowmass." (Sponsored by the NSF and the DOE). Published Rev. Mod. Phys.

Outcomes and themes:

1. The research roadmap is well advanced.
2. What was a relatively small field is large and growing rapidly.

What candidates made it into CF3's radar?

All dark-matter candidates, except for one.

1. Candidates came from lists generated by organizers, presentations and discussions at workshops, contributed white papers and comments (we've received very many comments).
2. There are many possible candidates.
3. To make it into our list, a candidate had to be sensible dark matter. That is, it needs to be created somehow and satisfy dark-matter observables. For instance, the light neutrino failed the dark-matter observable requirement.
4. The candidate needed to be injected into cosmology; it needs to be created with about the right amount and be the dark matter. Some candidates are rather well worked out, some are not. But there has to be a story. For instance, black holes re-entered the list with ideas to tune the black-hole mass function and yield during inflation.
5. Even then, new candidates and ideas appeared. For instance, "atomic" hidden-sector dark-matter.
6. The special role of the axion: Highly motivated, worked-out phenomenology.
7. CF3 has overlaps with IF5 "New light, weakly-coupled particles"; IF5 conveners choose to build around dark-matter. Some overlaps with CF6 "Cosmic particles & fundamental physics".

CF3 Document Overview (1)

Well-advanced from workshops & publications

Introduction

Theoretical motivation

General discussion of dark matter properties

- Particle physics considerations

- Astrophysical observations and insights

The landscape of candidates

- Asymmetric dark matter

- “Atomic” dark matter (exotic particle bound states)

- Axion

- Black holes

- Mirror dark matter

- Self-interacting non-WIMP dark matter (cusp vs core)

- Sterile neutrinos

- Superheavy dark matter (e.g. wimpzillas, strangelets)

- Superlight dark matter (NMR sub eV axion)

- Supersymmetric Q-balls and the products of their decays

- Supersymmetry’s non-WIMP candidates

Document Overview (2)

Key experimental technologies: the current status

- Direct detection

- Indirect detection

Experimental technology R&D, and future directions

Theory challenges

Concluding remarks

A Romp through some DM Candidates

Now to give some flavor for the range of candidates and the various issues.

Asymmetric Dark Matter

Asymmetric dark matter models are based on the hypothesis that the present-day abundance of dark matter has the same origin as the abundance of ordinary matter: an asymmetry in the number densities of particles and antiparticles.

Petraki & Volkas 2013

Possible signatures:

Search for extra early universe annihilation radiation

Search for radiation from halos

New particles (extra gauge bosons or scalars)

Induced nucleon decay

DM decays with charge asymmetry

Capture in stars and star seismology and evolution

Question: What's the research path for ADM?

Axions: Probably most well-studied non-WIMP dark-matter

PQ vs non-PQ

Terrestrial vs astrophysical

Terrestrial

RF-cavity →

Laser-shining light through walls

Laser-dichroism & birefringence

Short-distance spin-mass gravity

Astrophysical

Energy transport-red giants

Energy transport-sun

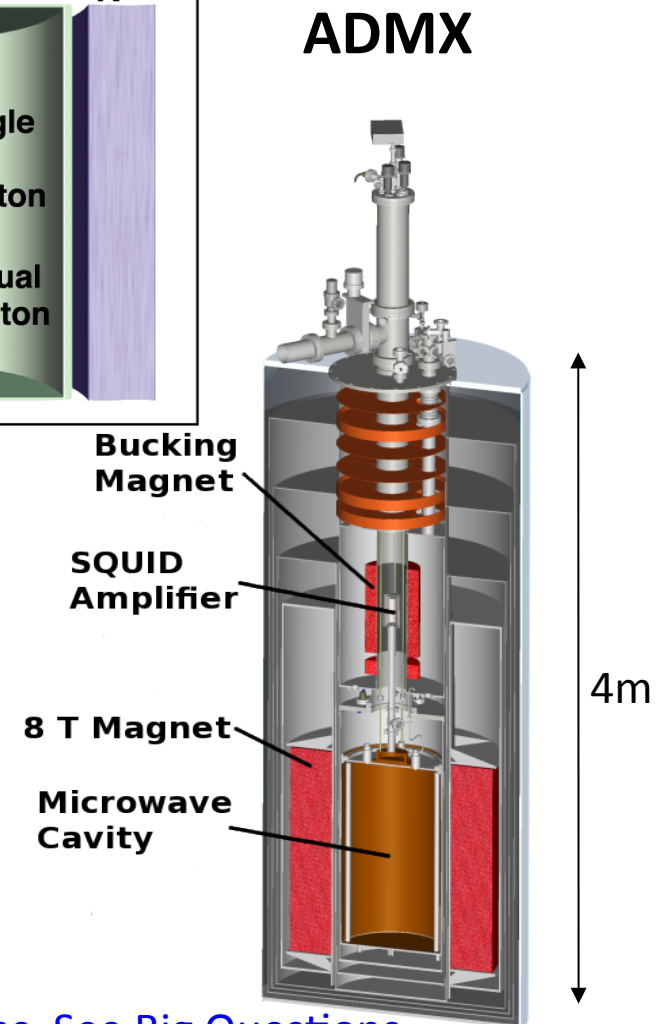
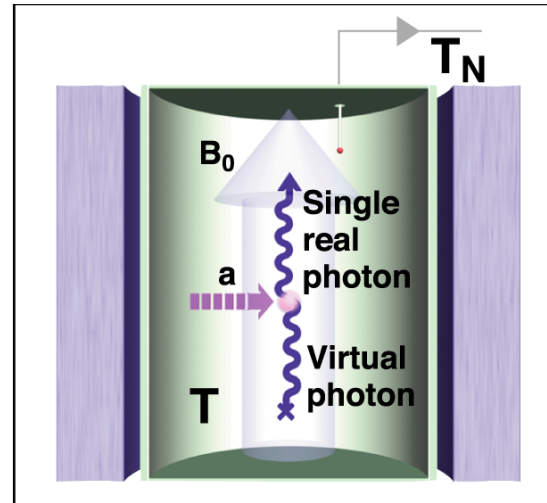
White dwarf cooling

Neutrinos from Snae

Direct detection of solar axions

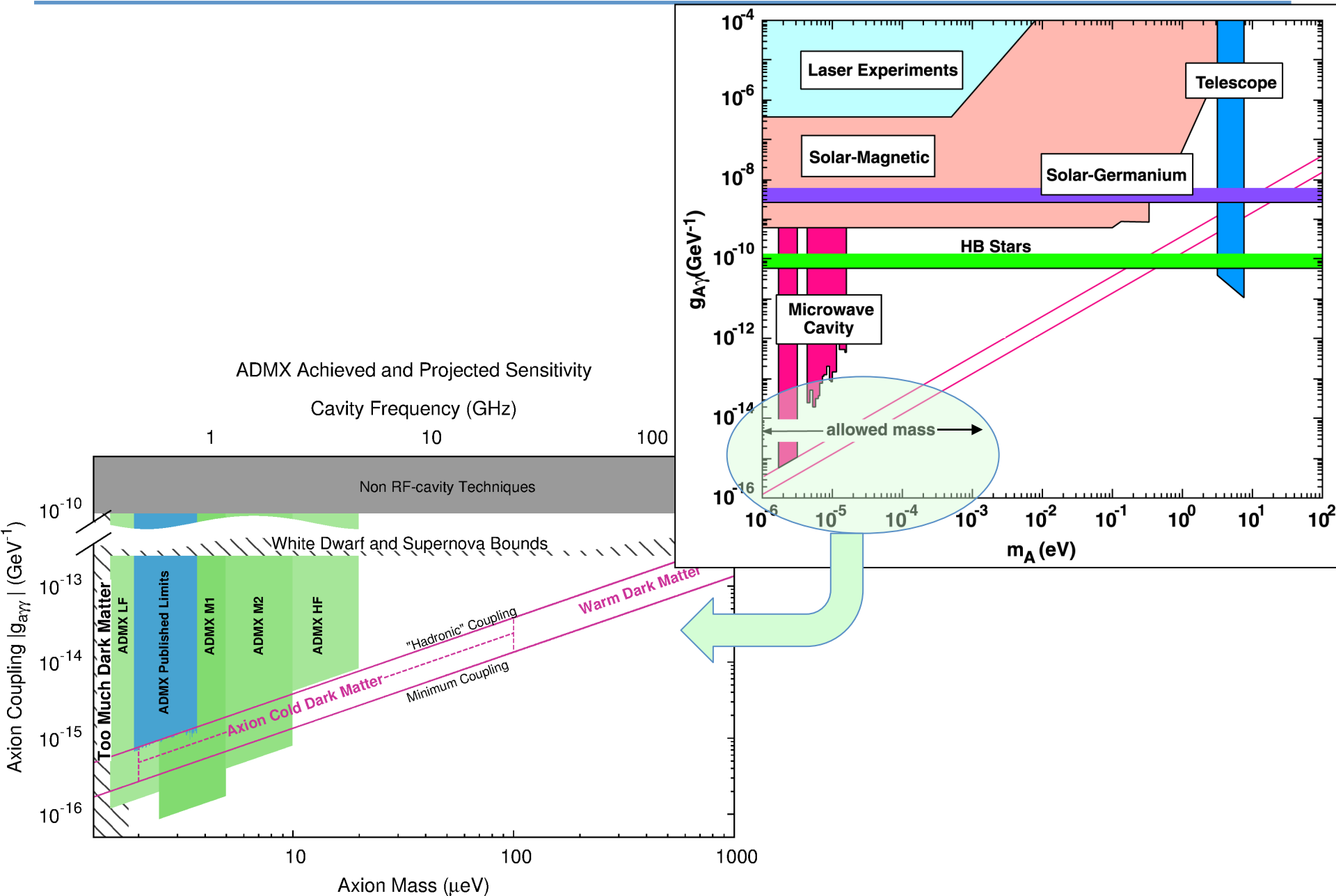
Optical and radio telescope searches

Propagation of astrophysical photons



Comment: Well motivated. Well-planned future programs. See Big Questions.

RF-Cavity Experiments Most Sensitive to QCD DM Axions



Mirror Dark Matter

“Mirror dark matter is a special case of asymmetric dark matter. The basic idea is that despite the $V - A$ character of weak interactions, the true microscopic theory of fundamental interactions might be completely symmetric under spatial inversion. In its purest form, both the Lagrangian and the vacuum are parity symmetric, differentiating mirror matter models from left-right symmetric models. While the latter have parity-invariant Lagrangians, experimental constraints force one to spontaneously break that discrete symmetry. Mirror dark matter has been argued to provide a compelling explanation for the results of DAMA, CoGeNT, CRESST and, most recently, CDMS/Si.” Foot & Volkas 2013

Mixing with normal matter leads to scatter/recoil

Theory issues: self interaction, e.g., explain spherical halos.

Key Question: Is MDM viable?

Key Question: What's the research path for MDM?

Black-Hole Dark Matter

Primordial BHs have issues with halo content mass-function and production rate.

Example: Recent theoretical (“double inflation”) Ideas to explain narrow mass function

Evades BBN constraints.

Non-exotic, interacts gravitationally

Astrophysics

- micro-, pico-, femto-lensing of quasars

- milli-lensing of GRBs

- Distortion of the CMB

- Disruption of binaries, globular clusters

- Disruption of neutron stars

- Heating of Milky Way disk

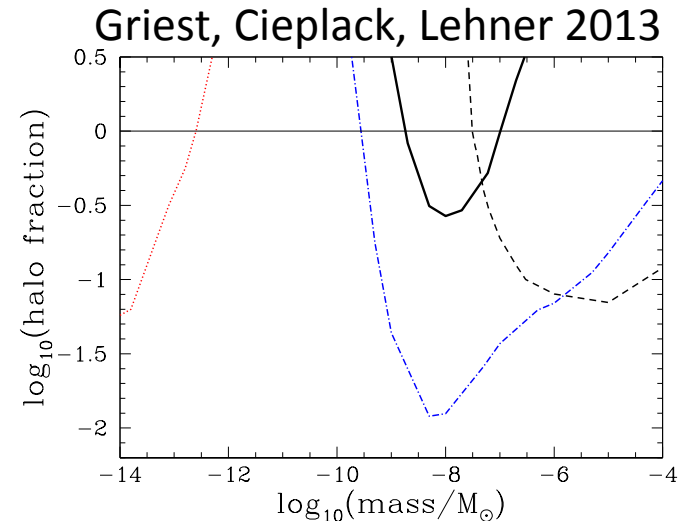


Fig. 6.— Upper limits (95% C.L.) on PBH DM from non-observation of PBH microlensing in two years of Kepler data. The solid black line is our new limit, the dashed black line is the previous best limit (Alcock, et al. (1998)), the blue dot-dash line is the theoretical limit from Paper II, and the red dotted line is the femtolensing limit from Barnacka, et al. (2012). The black horizontal line indicates a halo density of 0.3 GeVcm^{-3} .

Key Question: What's responsible for the overdensities leading to BHs?

Key Question: Are, e.g., finely-tuned scalar fields a problem?

Key Question: What's the research program going forward?

SuperSymmetric Q-Balls and the Products of their Decays

Q-balls: Solitons in SUSY. There's a new $U(1)$ symmetry with a new charge Q .

Q-ball properties depend on details of SUSY symmetry breaking.

Need details of production in the early universe.

Extremely heavy: $M > 10^{12}$ baryons, big objects with big cross sections.

Copious pion emission on, e.g., entering atmosphere.

A refinement: Can decay into LSPs: provides mechanism for ratio of VM to DM.

Comment: Of special interest to CF6.

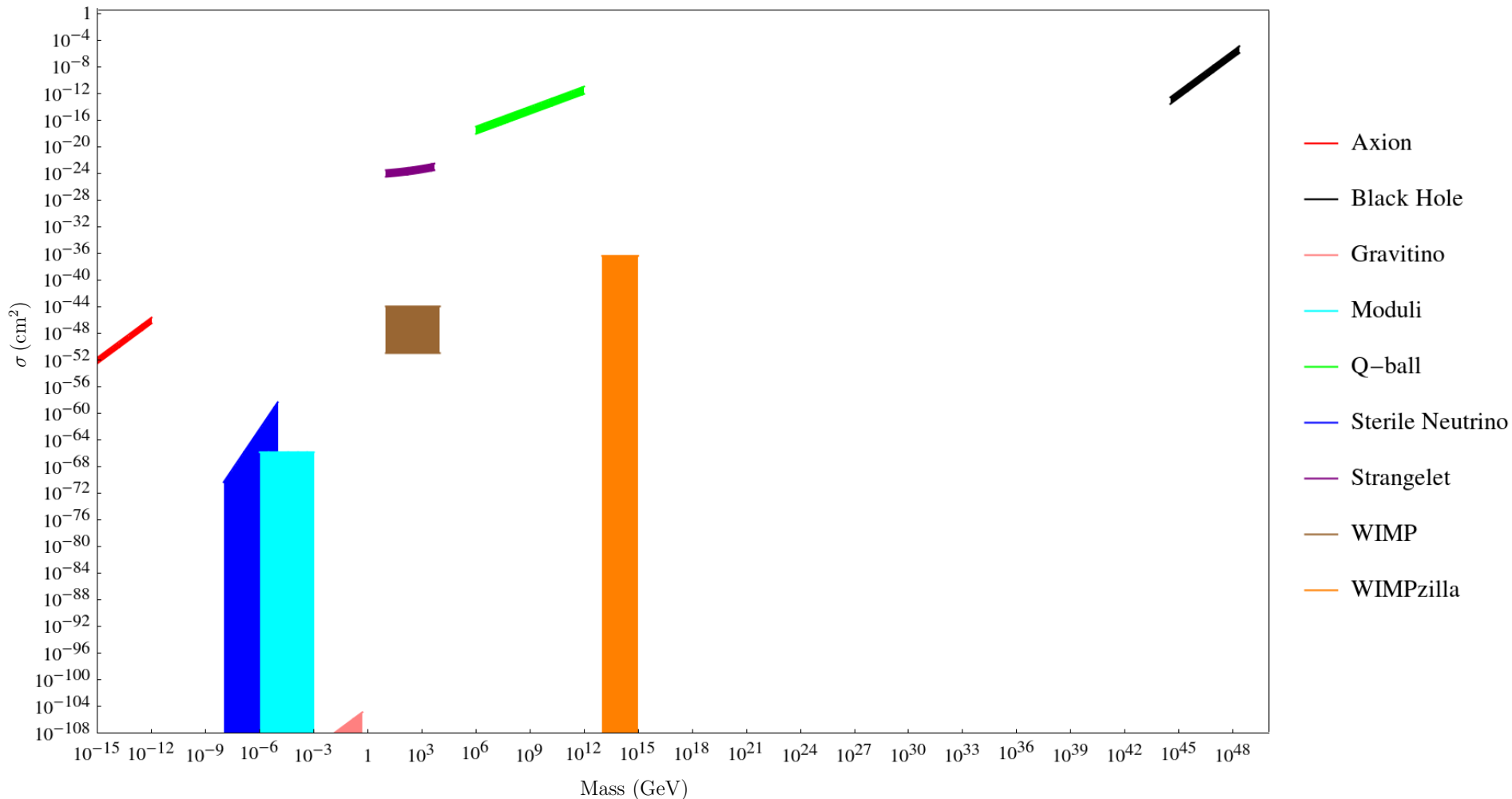
Key Question: Is there a carefully worked-out Q-ball cosmology?

Key Question: Same question with decay products?

Key Question: What's the research program going forward (CF6)?

The Large Number of CF3 Candidates: wide range of masses and couplings

Cross Section (Xenon for Reference)



Document preparation going forward

We've solicited expert contributions for most sections.

We're updating those contributions with your contributions from your comments, emails and presentations at the meetings.

We're posting drafts

([link to Snowmass2013/CosmicFrontier/CF3](#))

Most important for that draft: We need to know what's missing, what's done wrong, ensure dark-matter research appears somewhere (e.g., some weakly-interacting scalars are considered in Intensity Frontier).

Identified theory challenges: Not specifically CF3

Structure formation

n-body simulation and NFW halo profiles?

n-body simulation and fine structure in halos?

Axions and radiation from topological strings

What axion mass gives sensible Ω_m ?

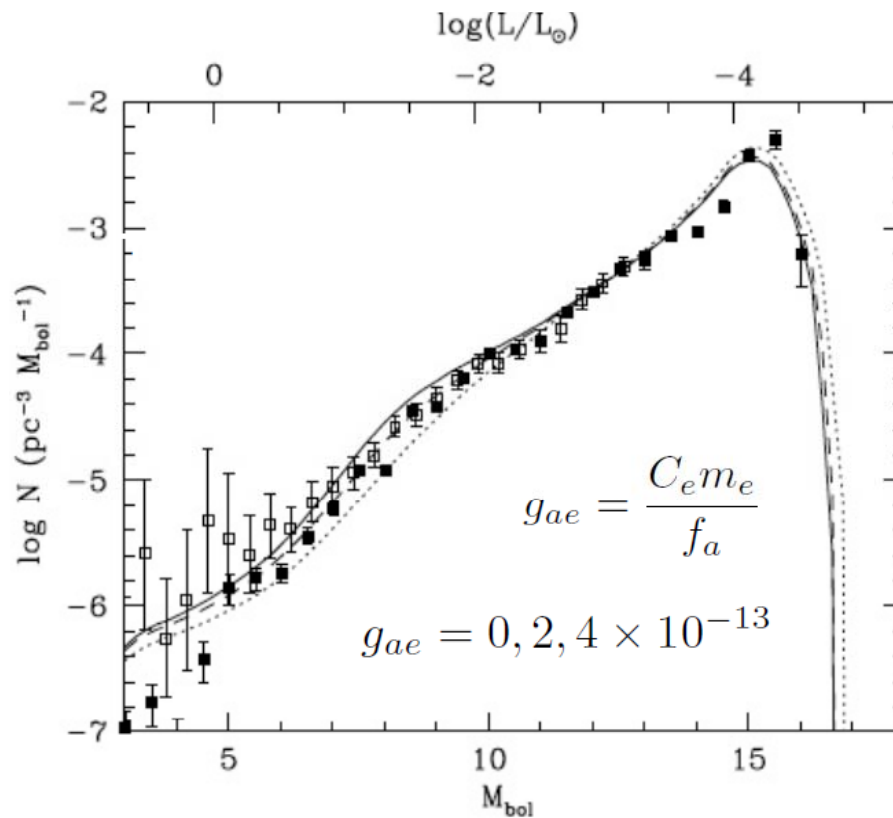
LHC

Axinos, Saxinos and f_{PQ}

Theory challenges

White dwarfs:

Can we understand cooling?

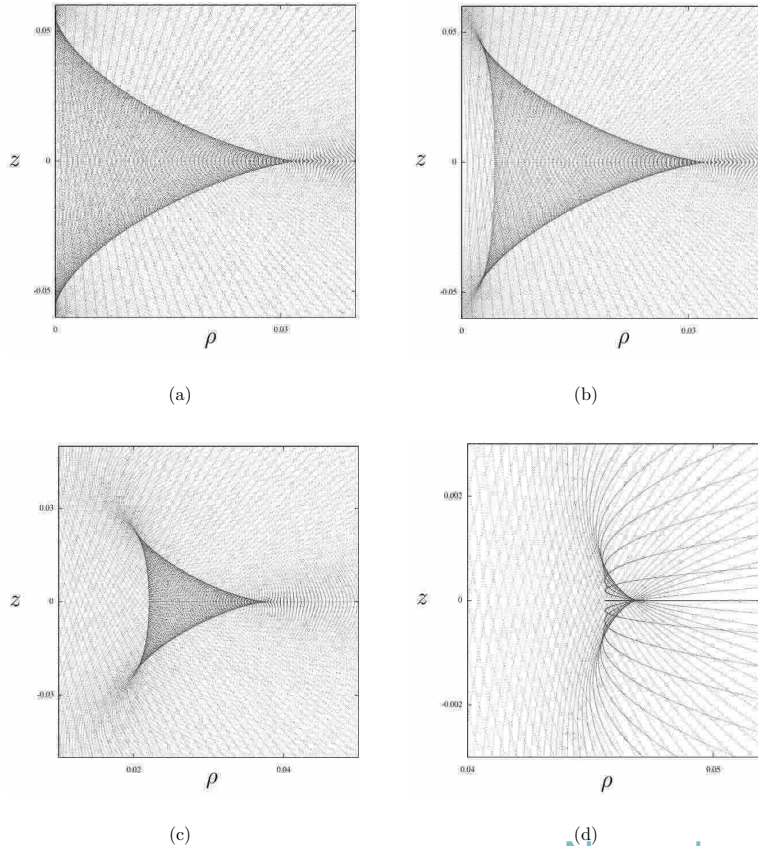


Isern et al., 2010

Theory challenges

Axion Bose-condensates & structure

Is the dark matter a Bose condensate?

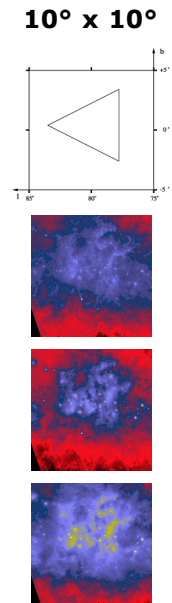


(d) Nararajan & Sikivie, 2005

FIG. 13: Cross sections of the inner caustics produced by the axially symmetric initial velocity field of Eq. (27) with $g_1 = -0.033$, and (a) $c_1 = 0$, (b) $c_2 = 0.01$, (c) $c_3 = 0.05$, (d) $c_3 = 0.1$. Increasing the rotational component of the initial velocity field causes the tent caustic (a) to transform into a tricuspid ring (d).

For instance:
Look where $n=5$ ring would be
in our galaxy
[Skyview virtual observatory](#)

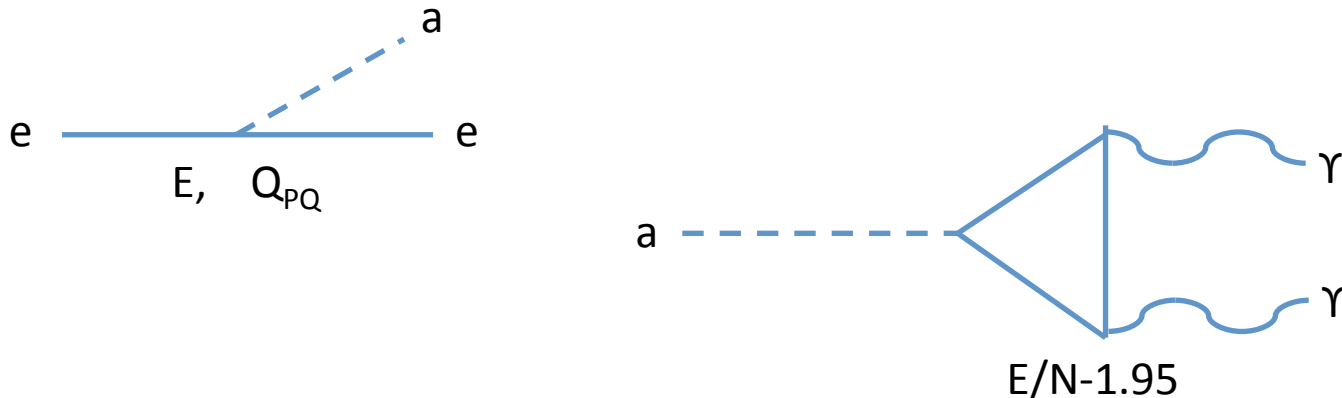
Triangular
Feature
Locator



Addressing Big Questions for CF3

CF13. Clarify the uncertainties in the expected axion detection rates: Particle physics: for a given mass, what is the lowest possible coupling? If there is no lower bound, are there values beyond which the models get qualitatively more fine-tuned and the search becomes less motivated? Astrophysics: can there be large variations local density? If so, how do these modify the experimental reach?

In general, there are large coupling uncertainties except for $a \rightarrow \gamma\gamma$



Could $E/N = 1.95$? I suppose yes, but...

Witten “can’t have couplings smaller than gravity.”

GUT axion gives $E/N=1/(3/8)$ in SM or something close to that.

If you believe in unification, there’s an accessible lower bound.

Big Questions for CF3

CF13. Clarify the uncertainties in the expected axion detection rates: Particle physics: for a given mass, what is the lowest possible coupling? If there is no lower bound, are there values beyond which the models get qualitatively more fine-tuned and the search becomes less motivated? Astrophysics: can there be large variations local density? If so, how do these modify the experimental reach?

The average local DM density is reasonably well-known (0.2 to 0.6 GeV/cc).

The velocity field is less well known. This uncertainty does not much effect axion searches, but the velocity field leaves a characteristic imprint on axion DM searches.

There could be a local spatial or spectral excess of DM: this could greatly enhance the search potential of DM searches.

Big Questions for CF3

CF14. What is the target range for axion mass and coupling, and how are those determined?

For PQ DM Axions: m_a 1 to 100 μeV . The coupling is $> \text{GUT (DFSZ)}$ (See question CF13). The lower mass bound comes from overclosure: One would need to worry about “anthropic axions”. The upper mass bound comes from various arguments applied to SN1987a rather robustly, plus white dwarf cooling: The WD cooling has substantial model dependence but is orthogonal to the SN1987a bound.

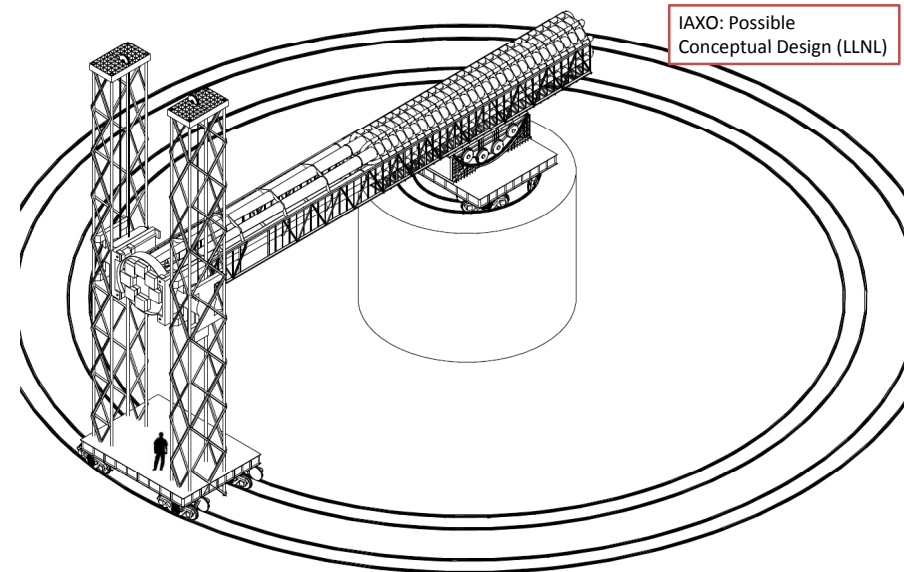
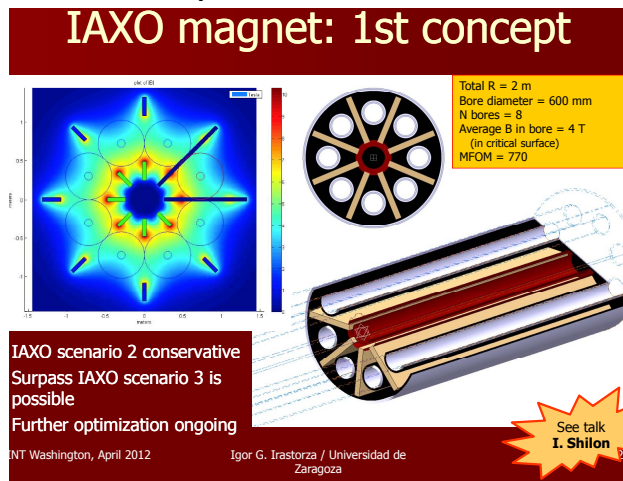
For non-PQ axions, the masses and couplings are constrained by SN1987a and WD cooling. But otherwise the masses and couplings are relatively unconstrained.

Big Questions for CF3

CF15. What are the most promising techniques to extend searches for non-WIMP dark matter?

The following tend to reappear:

1. Theory initiatives to better understand photon propagation in extragalactic space and white dwarf cooling.
2. Theory initiative to understand whether Bose dark matter has a distinctive signature.
3. RF cavity axion searches.
4. Laser ALP experiments.
5. Solar ALP & axion experiments.



Conclusion: focus returns to three key technologies

